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60 Garden Street, Cambridge, MA 02138

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FINAL TECHNICAL REPORT NAGW-1596

Title of Investigation: *Absolute Transition Probabilities of Lines in the Spectra of Astrophysical Atoms, Molecules, and Ions*

Principal Investigator: W. H. Parkinson  
Harvard College Observatory  
60 Garden Street, MS-50  
Cambridge, MA 02138  
617/495-4865 (fax -7455)

Co-Investigators: Peter L. Smith, Harvard College Observatory  
Kouichi Yoshino, Harvard College Observatory  
Glenn Stark, Wellesley College

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## 1. INTRODUCTION

The laboratory astrophysics research program supported by NAGW-1596 comprised analysis of spectra and measurements of fundamental atomic and molecular data at ultraviolet (UV), vacuum ultraviolet (VUV), and extreme ultraviolet (EUV) wavelengths. We measured transition probabilities of molecular rotational lines that have been (or could be) used for detection of molecules in diffuse and translucent interstellar clouds and for determination of molecular column densities there. In addition, we determined line wavelengths and assignments, linewidths, predissociation probabilities, and continuous absorption cross sections. These molecular parameters are essential for theoretical descriptions of the abundances and excitations of interstellar molecules and for comparisons of observations with predictions. Many of the molecules studied have been observed in diffuse interstellar clouds with the GHRS on HST.

In our studies of atoms and ions of astrophysical interest, we measured  $A$ -values for intersystem (spin-changing) and other weak lines in low- $Z$  singly- and doubly-charged ions. Plasma diagnostic methods and column density determinations require accurate and complete atomic parameters, in particular, collision strengths and  $A$ -values. No measurement had been made of astrophysically interesting intersystem line  $A$ -values for light ions until we began our laboratory program. Differences between our measured  $A$ -values and calculated ones have motivated revisions to the latter that have resulted in better agreement.

## 2 ACCOMPLISHMENTS OF THE RESEARCH PROGRAM

In the past grant period we completed and initiated a number of measurements of interest to astronomers. The resulting, published refereed papers are listed in Section 2.2, and the reports, reviews, and presentations are described and listed in Section 2.3. A number of projects still in progress are described in Section 2.1.

### 2.1 Work in Progress

It was suggested by Morton (personal communication) that absorption by interstellar  $H_2O$  would probably be detected with the GHRS on HST. Because our earlier measurements (Smith & Parkinson 1978, Smith *et al.* 1981) of  $f$ -values for the VUV bands of  $H_2O$  were made by the problematic photographic method, we have undertaken remeasurements of two absorption bands, C-X at  $\sim 124$  nm and F-X at 116 nm by using the photoelectric method. These measurements are almost complete and analyzed and the work will soon be prepared for publication.

We have for similar reasons remeasured photoelectrically the absorption cross sections of the C(0) - X(0) and C(1) - X(0) bands of HCl. Our results will be prepared for publication shortly, but have been provided to and used by Federman *et al.* (1995) to analyze absorption at 129 nm by HCl in spectra recorded by GHRS of clouds in the line of sight to  $\zeta$  Ophiuchi.

Lambert *et al.* (1994) have reported the detection of intersystem bands of CO, [eg. a' (17)-, a' (14)-, d(12)-, d(7)- and e(4) - X(0)] with GHRS in observations toward  $\zeta$  Ophiuchi. They point out that uncertainty in the  $f$ -values for the bands is the largest source of uncertainty in their results. We have measurements of the photoabsorption cross sections of some of these intersystem bands -- d(12) - X(0), d(7) - X(0) and e(4) - X(0) -- at 295 K. Analyses of these data and additional measurements of bands at lower temperatures are planned.

## 2.2 Publications

- High-Resolution Spectra and Photoabsorption Coefficients for Carbon Monoxide Absorption Bands Between 94.0 nm and 100.4 nm*, K. Yoshino, G. Stark, P. L. Smith, W. H. Parkinson & K. Ito, *ApJ* **369**, 574 (1991).
- Laboratory Absorption Spectra of Molecules at Interstellar Cloud Temperatures: First Measurements on CO at 97 nm*, P. L. Smith, G. Stark, K. Yoshino, K. Ito & M. H. Stevens, *A&A Lett.* **252**, L13 (1991).
- High-Resolution Photoabsorption Cross Sections of  $E^1\Pi - X^1\Sigma^+$  Vibrational Bands of  $^{12}\text{CO}$  and  $^{13}\text{CO}$* , G. Stark, Peter L. Smith, K. Ito & K. Yoshino, *ApJ* **395**, 705 (1992).
- Recalibration of the Absorption/Photodissociation Spectra of CO and its Isotopes Between 91 and 115 nm*, M. Eidelsberg, J. J. Benayoun, Y. Viala, F. Rostas, Peter L. Smith, K. Yoshino, G. Stark & C. A. Shettle, *A&A* **265**, 839 (1992).
- Absorption Band Oscillator Strengths of  $N_2$  Transitions Between 95.8 and 99.4 nm*, G. Stark, P. L. Smith, M. H. Stevens, K. Yoshino, K. Huber & K. Ito, *J. Chem. Phys.* **97**(7), 4809 (1992).
- Radiative Lifetime of the  $3s3p^3^5S_2^0$  Metastable Level of  $P^+$* , Anthony Calamai, Xiaofeng Han & William H. Parkinson, *Phys. Rev. A* **45**, 2716 (1992).
- High-Resolution Absorption Cross Measurements of Carbon Monoxide at 20 K Between 96.7 and 98.8 nm*, G. Stark, K. Yoshino, P. L. Smith, J. R. Esmond, K. Ito & M. H. Stevens, *ApJ* **410**, 837 (1993).
- Measurements of Radiative-Decay Rates of the  $2s^22p(^2P^o) - 2s2p^2(^4P)$  Intersystem Transitions of C II*, Z. Fang, V. H. S. Kwong, J. Wang & W. H. Parkinson, *Phys. Rev. A* **48**(2), 1114, 1993.
- Radiative Lifetimes of the  $2s2p^2(^4P)$  Metastable Levels of N III*, Z. Fang, V. H. S. Kwong & W. H. Parkinson, *ApJ* **413**, L141 (1993).
- Transition Probabilities for the  $3s^23p^2P^o - 3s3p^2^4P$  Intersystem Lines of Si II*, A. G. Calamai, P. L. Smith & S. D. Bergeson, *ApJ Lett.* **415**, 59 (1993).
- High-Resolution  $f$ -value Measurements for A-X Bands of CO with  $11 \leq v' \leq 14$* , P. L. Smith, G. Stark, K. Yoshino & K. Ito, *ApJ Lett.* **431**, L143 (1994).
- High-Resolution Absorption Cross Measurements for Supersonic Jet-Cooled CO Between 92.5 and 97.4 nm*, K. Yoshino, G. Stark, J. R. Esmond, P. L. Smith, K. Ito & T. Matsui, *ApJ* **438**, 1013 (1994).
- Transition Probabilities for the  $3s^23p^2^3P_{2,1} - 3s3p^3^5S$  Intersystem Lines of S III*, Claas Heise, Peter L. Smith & Anthony G. Calamai, *ApJ Lett.* **451**, L41 (1995).

## 2.3 Reports, Reviews & Presentations

Peter L. Smith served the UVGA Branch in 1993 by conducting a survey of Branch-supported astronomers who use atomic and molecular parameters. He attempted to determine whether these astronomers: (i), were aware of the extent of UVGA Branch support of laboratory astrophysics, (ii), believed that the level of support for such research was adequate, and (iii), had, or expected to have,

atomic and molecular data needs that were unmet. A report to the UVGA MOWG was presented in April 1994. Smith was appointed to the MOWG in 1994 and served until it was disbanded in Nov. 1995. Smith served in 1991 as a member of the Theory & Laboratory Astrophysics Panel of the Astronomy & Astrophysics Survey Committee of the National Research Council.

Parkinson served as Vice-President of IAU Commission 14 (Atomic & Molecular Data) 1991-1994 and as Chair of Working Group 5 (Molecular Structure & Transition Data) of that Commission 1988-1994. The triennial reports of this Working Group have been prepared by Parkinson for publication in *Reports on Astronomy XXIA*, 1991 and *XXIIA*, 1994. Smith continues to serve as Secretary of Comm. 14. Both are on the Organizing Committee for Commission 14 activities. Parkinson is Commission 14 President for the next three years.

*Ultraviolet Intersystem A-values*, W. H. Parkinson & Peter L. Smith, in *THE ANALYSIS OF EMISSION LINES*, ed. R. Williams & M. Livio [Cambridge Univ. Press] (1995).

*High Resolution FUV and VUV Laboratory Spectroscopy of Interstellar Molecules*, Peter L. Smith, at a Special Session at the April 1995 meeting of the American Physical Society.

*Atomic Data for Modelling the Optical Spectra of Supernovae: the Gray Literature*, Peter L. Smith in *NUCLEAR PHYSICS IN THE UNIVERSE*, ed. Strayer & Guidry [London: IOP] 387 (1993).

*Laboratory Absorption Spectra of Interstellar Molecules: Measurements on CO and N<sub>2</sub> at ~ 30 and 295 K*, G. Stark, P. L. Smith, K. Yoshino, W. H. Parkinson, K. Ito & M. H. Stevens, *UV & X-RAY SPECTROSCOPY OF LABORATORY & ASTROPHYSICAL PLASMA*, ed. E. Silver & S. Kahn [Cambridge University Press] 165 (1993).

*Atomic & Molecular Data for Space Astronomy: Needs and Availability*, ed. Peter Smith & Wolfgang Wiese [Springer-Verlag] in *LECTURE NOTES IN PHYSICS SERIES* (1992).

*High-Resolution Vacuum Ultraviolet Laboratory Spectroscopy of Astrophysical Molecules*, in *UV AND X-RAY SPECTROSCOPY OF ASTROPHYSICAL AND LABORATORY PLASMAS*, ed. K. Yamashita & T. Watanabe [Tokyo: Universal Academy Press] in press (1996?); invited paper.

*Fourier Transform of Emission Line Spectra at VUV Wavelengths*, A. P. Thorne, G. Cox, P. L. Smith, W. H. Parkinson & R. C. M. Learner, in *LABORATORY AND ASTRONOMICAL HIGH RESOLUTION SPECTRA*, eds. A. J. Sauval, R. Blomme & N. Grevesse, *ASP Conf. Ser.* **81**, 235 (1995).

*Beamsplitters for VUV Fourier Transform Spectroscopy*, A. P. Thorne, G. Cox, P. L. Smith & W. H. Parkinson, in *ULTRAVIOLET TECHNOLOGY V*, ed. R. H. Huffman, *Proc. S.P.I.E.* **2283**, 58-64 (1994).

*A Comparison of Imaging Fourier Transform with Grating Spectrometry for Tridimensional Spectroscopy*, P. L. Smith, A. P. Thorne & W. H. Parkinson, in *TRI-DIMENSIONAL SPECTROSCOPIC METHODS IN ASTROPHYSICS*, ed. G. Compte & M. Marcelin, *ASP Conf. Ser.* **71**, 328 (1995).

### 3. REFERENCES

- Federman, S. R., J. A. Cardelli, E. van Dishoeck, D. L. Lambert & J. H. Black 1995, *ApJ* **445**, 325.  
Lambert, D. L., Y. Sheffer, R. L. Gilliland & S. R. Federman 1994*i*, *ApJ Lett.* **420**(2), 756.  
Smith, P. L. & W. H. Parkinson 1978, *ApJ Lett.* **223**, 127.  
Smith, P. L., K. Yoshino, H. E. Griesinger & J. H. Black 1981, *ApJ* **250**, 166.